A Novel MEMS Microcrankshaft Using Thermal Actuators

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ABSTRACT

Thermal actuators are employed to generate torque and rotation perpendicular to the plane of the substrate. The proposed design and fabrication process of a "microcrankshaft" is presented using the Sandia Ultra-planar Multi-level MEMS Technology V (SUMMiT V) foundry service. Possible applications include propellers, motors, and gears in planes of rotation previously unused.

INTRODUCTION

Traditional MEMS designs are strongly constricted by the layered polysilicon fabrication process. Most structures that rotate do so parallel to the plane of the substrate. For example, fixed-axle and self-constrained pin joints and four-bar linkages[1] provide rotation in the z-direction (assuming coincidence between the x-y and substrate planes). Others use hinges and locks or *in situ* actuators to assemble devices into upright positions away from the substrate[3,4], resulting in an arduous pre-operation assembly process that requires manipulation of substrate structures using micromanipulators. No devices have been introduced that produce rotation in an arbitrary plane perpendicular to the z-direction, i.e., in the plane of the substrate, that do not require assembly.

A crankshaft driven by thermal actuators provides a plausible method of producing rotation in a new plane. Because thermal actuators lie in the plane of the substrate, the displacements they produce can be transformed into torque via a rotating shaft. Here, we discuss the design of the different components of such a device, its proposed fabrication process, and the challenges associated with the torque produced by it.

DESIGN

The actuation of rotation with an axis parallel to the substrate poses many design challenges. Here, the application and design of the thermal actuators, bearings, and rotation cavity are discussed. A model of the device is shown in Fig. 1 for visual clarity.

Thermal Actuators

In this MEMS crankshaft application, thermal actuators provide linear, mechanical force somewhat analogous to that provided by pistons and combustion cylinders in an internal combustion engine. Thermal actuators were a natural choice over other linear MEMS actuators such as the comb drive[5] because of the thermal actuator's superior displacement and generation of force[6] or, in this application, torque.

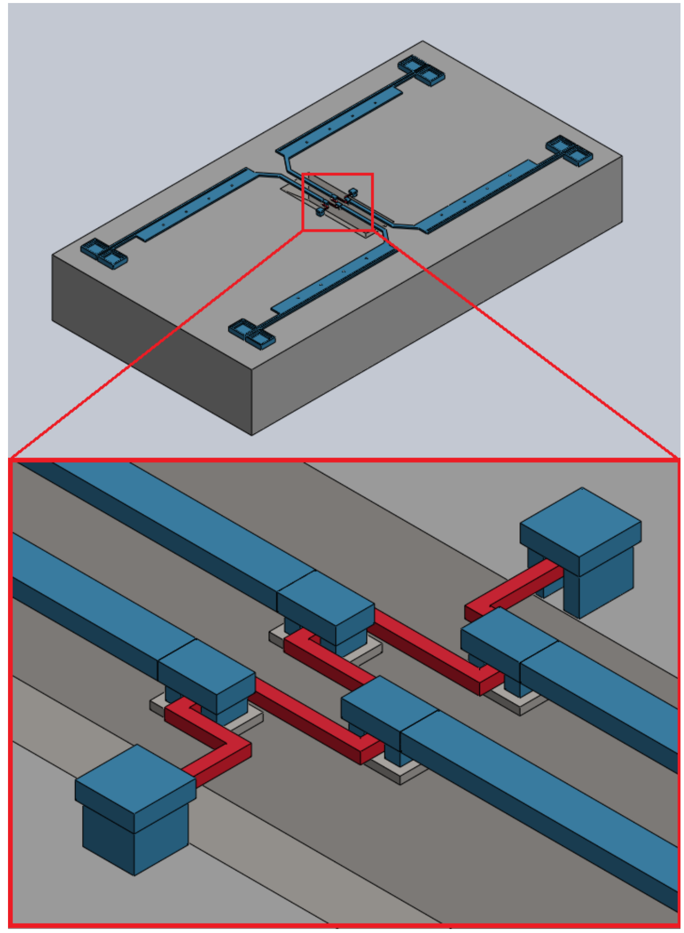

Fig. 1. Solid model of proposed crankshaft drive. The crankshaft and bearings are shown enlarged.

Both one-hot-arm[6] and two-hot-arm[7] thermal actuator designs are available, and in a crankshaft application where both high displacement and torque are desirable characteristics, the two-hot-arm design is more appropriate given its greater displacement and force. However, this work employs one-hot-arm thermal actuators for the simplicity of analysis.

Bearings

The bearings are a critical structure which allow the linear motion and forces from the thermal actuators to be transformed into the rotational motion and torques that drive the crankshaft. Due to the constraints of MEMS fabrication, this design uses plain bearings with a rectangular cross-section. This concept is derived from Pister's design of immobile microfabricated hinges which allows structures fixed to the substrate to be flipped upward for operation[8].

As both the portion of the crankshaft within the bearing as well as the bearing itself have rectangular cross-sections, care must be taken to ensure that there is enough play such that the crankshaft is able to rotate a full 360° without mechanical interference from the inner bearing surface. This is done by manipulating the thickness of the sacrificial oxide layers above and below the crankshaft polysilicon such that the cross-sectional diagonal of the crankshaft is no longer than the height or width of the bearing opening.

However, the thickness of sacrificial oxide should not be so significant as to introduce excessive slop in the bearing mechanism. In the SUMMiT V process, the full thicknesses of sacrificial oxide above and below the crankshaft MMPOLY2 provide ≥1.51 μm of vertical play throughout a full rotation. In order to make the bearing-crankshaft interplay tighter, this design entirely replaces SACOX3 with its dimple backfill, a feature unique to SUMMiT V[9]. Using the backfill, there can essentially be a SACOX3 layer only 0.4 μm thick. This is desirable both to dramatically decrease the amount of play but also to avoid the high degree of thickness variation associated with the SACOX3 layer. Fabrication processes introduce a standard deviation in SACOX3 thickness of 5400 Å, or 35% of the crankshaft thickness, an unacceptable degree of inaccuracy for this mechanism. The standard deviation of the SACOX3 backfill thickness, however, is only 53 Å. Assuming an MMPOLY2 thickness of 1.53 μm, this allows the crankshaft thickness in the horizontal direction to be 1.62 μm with a minimum shaft clearance of 17 Å, neatly resulting in a nearly square crankshaft cross section.

Crankshaft

The radius of rotation, and thus the output torque, is limited by the maximum possible displacement of the thermal actuators. Comtois[6] reports a maximum deflection of up to 16 μm, thus this design employs a radius of rotation of 8 μm. This in turn dictates the depth of the rotation cavity as well as the overall width of the crankshaft.

Because the bearings must be fabricated to envelop the crankshaft as discussed above, MMPOLY2 is the layer of structural polysilicon used to fabricate the crankshaft.

Rotation Cavity

Because the crankshaft is deposited only about 2 μm above the substrate but requires an 8 μm radius of rotation, space must be made for the crankshaft to rotate and bearings to travel. One method is to use Pister's hinges[8] to elevate the crankshaft and bearing assembly off the substrate, which would require a complex system of hinges as well as pre-operation assembly. A better option is to use bulk micromachining to etch a cavity in the substrate underneath the crankshaft after it has been fabricated. This requires the final surface-micromachined structures to be covered with a layer of protective oxide such that they are not also etched. A well-timed, anisotropic etch of the substrate forming {111} slopes will give the crankshaft the best chance of free rotation without hindrance from the substrate below.

For the etchant, a KOH system is ideal for this application. Not only is KOH highly selective in the (110) and (100) planes, but it also etches SiO_2, the protective layer in this etching process, slowly enough at a rate of 14 $^{Å}/_{min}$ to ensure that the protective oxide and polysilicon structures will survive the bulk micromachining process[10]. With a planned cavity depth of 20 μm, the etching process will require about 15 minutes, corresponding to non-problematic 21 nm of oxide etching.

FABRICATION

Fabrication of the microcrankshaft system occurs in two stages: surface micromachining of the main features, i.e., the thermal actuators, crankshaft, and bearings, and bulk micromachining of the rotation cavity. The surface micromachining is carried out using the SUMMiT V process, taking advantage of the higher mask alignment resolution of 0.5 μm over the MUMPs process as well as the dimple backfill option[9]. Bulk micromachining uses KOH to etch an inverted rectangular frustum cavity to allow sufficient space for shaft rotation. The process flow is shown in Fig. 2 which is not to scale and is only for visual and conceptual understanding.

Surface Micromachining Fabrication

(a): The nitride and thermal oxide layers are cut from underneath future structures that need to be entirely separated from the substrate (e.g., the bearings and crankshaft). The location of the planned rotation cavity is also cut. This is such that etchant in the later bulk micromachining step has access to the silicon substrate.

(b): Immediately, SACOX1 is laid down underneath future structures, e.g., bearings, crankshaft, thermal actuators. (The preceding MMPOLY0 layer is entirely etched). The oxide serves two purposes: to elevate structures off the substrate and protect the bearings from bulk micromachining etchant. All oxide layers henceforward will only be placed in areas that will effectively "coat" polysilicon structures that are to survive the bulk micromachining etching. This will allow the etchant to flow around oxide-coated polysilicon structures to attack the silicon substrate.

(c): MMPOLY1 forms the bottom layer of the bearings.

(d): The dimple backfill of SACOX2 defines the initial crankshaft-bearing play *underneath* the crankshaft. (The original 2 μm of SACOX2 are completely etched.)

(e): MMPOLY2 forms the crankshaft.

(f): The dimple backfill of SACOX3 defines the initial crankshaft-bearing play *above* the crankshaft. (The original 2 μm of SACOX3 is entirely removed.)

(g): SACOX3_CUT cuts windows in the two oxide layers to anchor the imminent MMPOLY3 layer.

(h): MMPOLY3 forms the majority of the structural elements: the pads and arms of the thermal actuators as well as the "roofs" and "walls" of the bearings.

(i): SACOX4 provides the final layer of protective oxide for shielding polysilicon structures from bulk micromachining etchant. (The subsequent MMPOLY4 layer is entirely etched.)

Bulk Micromachining Fabrication

(j): KOH attacks substrate that is not coated by either nitride or oxide. Etching occurs selectively along {111} planes downward. The resulting cavity allows full, uninhibited 360° rotation of the crankshaft and its bearings.

(k): All sacrificial oxide is etched, releasing all polysilicon structures.

ANALYSIS

Because this application is shaft based, a brief analysis of the torque output of this MEMS crankshaft is necessary. The torque generated can be expressed as

$$\tau = \left\|\vec{r} \times \vec{F}\right\| = rF\sin\theta\,. \qquad \text{Eq. 1}$$

Assuming that the force generated is proportional to the current driving the thermal actuator, an absolute cosecantic wave should be used to produce a constant torque. Unfortunately, infinite current is implausible nor would it generate a non-zero torque, thus the drive waveform must be simplified to peak at a current maximum limited by either the melting point of polysilicon or the buckling resistance of the drive beam.

In practice, however, the thermal actuators would most likely be driven by a squarewave input analogous to the forces produced by the pistons of a combustion engine. To maximize the peak torque, the thermal actuator should exert its maximum force when its horizontal displacement is 8 μm (corresponding to the maximum of $\sin\theta = 1$). There is little to no work in the literature characterizing thermal actuator force generated as a function of displacement; works[4,6] report 4.4 μN forces at 8 μm displacement and 25 μN at 1.6 μm, so here we will assume a force of 4.4 μN at 8 μm of displacement. Following Eq. 1, this gives a peak torque of 3.52×10^{-11} N·m or 35.2 μN·μm.

To depict the problematically uneven torque produced by this mechanism, Fig. 3 depicts the torque output of a system driven by a squarewave generating a

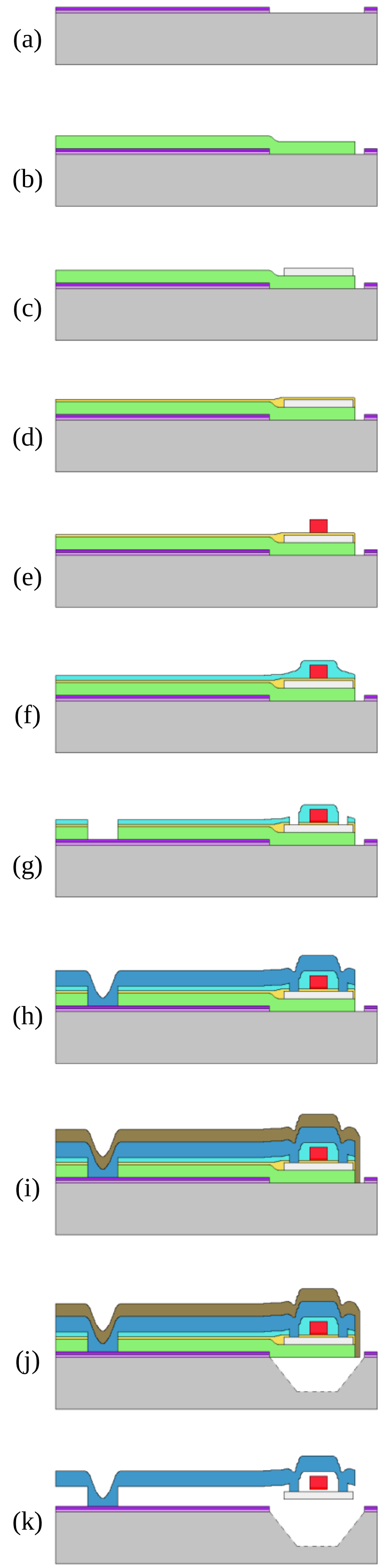

Fig. 2. Fabrication process flow diagram.

constant force of 4.4 μN. According to Fig. 3 of Comtois[4], this requires a drive current of 4 mA.

Possible methods to rectify this unevenness in torque are additional actuators acting in the vertical direction or a variable drive wave such as the cosecant wave. Arranging thermal actuators to be parallel rather than antiparallel may also alleviate issues related to asymmetry.

FUTURE WORK

This design is presented only as a proof-of-concept design, and considerable refinement and redesign must be done before a working mechanism can be fabricated. Issues or concerns that were not addressed or not fully addressed earlier are mentioned here.

Bearing Slop

If the bearings are not designed correctly, the amount of slop between the bearings and crankshaft may become a significant portion of the thermal actuator displacement. This would cause lag in the force transfer from the thermal actuators to the crankshaft and possibly prevent the crankshaft from rotating continuously in one direction. Here, with SUMMiT V's mask resolution of 0.5 μm and the use of dimple backfill thicknesses, there should be no issues with excessive slop in the vertical or horizontal directions.

Beam Width Variation

The accuracy of the crankshaft's width is of importance due to the slop concern outlined earlier. The SUMMiT V design manual[9] notes that beam widths in the MMPOLY2 layer are on average inaccurate by 13%, a significant amount with regards to mechanical play. A more detailed study of SUMMiT V beam widths must be performed to ensure that the crankshaft is fabricated with sufficiently accurate dimensions.

Continuity of Rotation

Thermal actuators are linear, one-dimensional actuators arranged antiparallel to one another in this device. This results in a point in the crankshaft's rotation (at $n\pi$ degrees for $n \in \mathbb{Z}$) where no torque is produced and the crankshaft may cease to rotate. Similarly, the crankshaft may reach this point and reverse direction, rotating in a direction opposite the initial rotation. The rotational inertia of the crankshaft theoretically aids in continuing its rotation, but considering the crankshaft's size and mass, its rotational inertia is negligible. Possible solutions to the continuity problem are offsetting the thermal actuators and bearing vertically to eliminate the zero-torque point, arranging thermal actuators in parallel rather than in antiparallel, or adding timed actuating forces in the vertical direction.

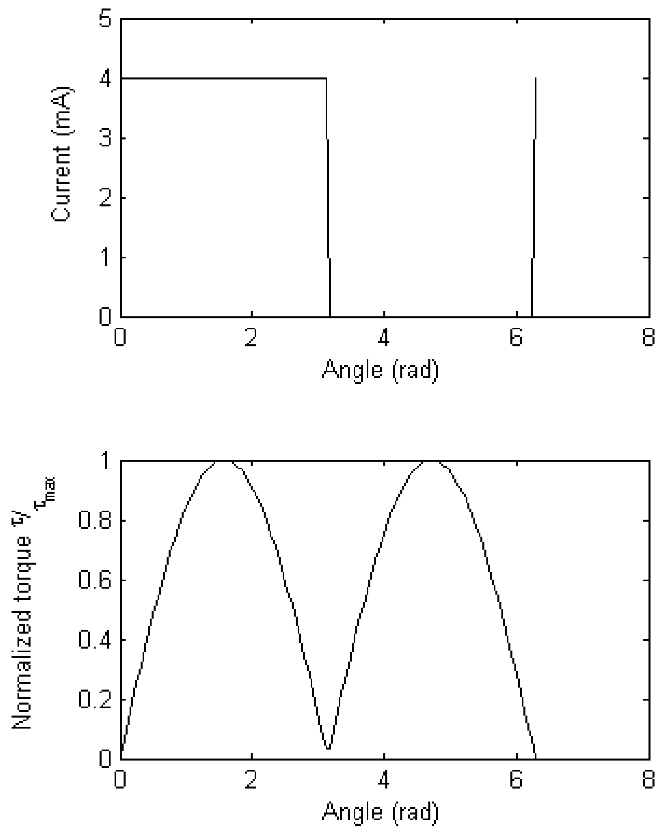

Fig. 3. Representative plots of current vs. angle of rotation and normalized output torque vs. angle.

Thermal Actuator Characterization

A more complete knowledge of the mechanics of thermal actuators is necessary to properly design and optimize a microcrankshaft system. In particular, the thermal actuators used in this application must be tested for force versus displacement data and force versus current data. The maximum possible force exerted at a given displacement is particularly useful for this project.

Secondly, characterization of the forces exerted by the thermal actuator as it retracts to its zero-deflection position is critical to analyzing the torque produced throughout a full rotation. The symmetry of the forces produced by the thermal actuator as it extends and retracts is very important to torque smoothness.

Thirdly, thermal actuators are studied largely for the displacements and forces they produce. This particular application is also invested in the velocity at which the actuation point moves given a certain driving current. This in turn can be used to characterize a rotational speed or RPM value for the crankshaft, a key parameter in any motor application. An ideal thermal actuator will produce a constant force independent of displacement and linearly displace at a constant rate. Actual rate of displacement, i.e., velocity, will depend upon the rate of applied current and will involve an analysis in heat transfer.

Fourth, most thermal actuator applications only flex the arms in a plane of rotation parallel to the substrate. The crankshaft application, however, also flexes them slightly along the axis running parallel to and between the hot and cold arms of the actuator. This additional flexing in a new plane is due to the vertical displacement of the thermal actuator tip. This vertical displacement may be deemed negligible in comparison to the length of the arm of actuation. Regardless, a fracture and fatigue study of the new rotation should be carried out to verify this.

Finally, a study of the compatibility of two-hot-arm actuators with this design should be performed. As the two-hot-arm actuators exhibit larger displacement and forces than do the one-hot-arm actuators, they may prove considerably more effective at producing larger torques.

CONCLUSION

This work presents a preliminary design of a thermally actuated microcrankshaft that produces rotation in a plane perpendicular to the silicon substrate. This involves a new application of linear thermal actuators and design of simple mechanical bearings inspired by MEMS hinges. The proposed fabrication process uses the SUMMiT V process as well as bulk micromachining with KOH as an anisotropic etchant. Early calculations estimate a peak torque output of 35.2 μN·μm with an applied current of 4 mA.

REFERENCES

1. L. Fan, Y. Tai, R. S. Muller, "Integrated Movable Micromechanical Structures for Sensors and Actuators", *IEEE Transactions on Electron Devices*, vol. 35, no. 6, June 1988
2. D. J. Dagel *et al.*, "Out-of-plane, rotary micromirrors for reconfigurable photonic applications", *Proc. SPIE*, vol. 4983, 114-121
3. T. Akiyama, D. Collard, H. Fujita, "Scratch Drive Actuator with Mechanical Links for Self-Assembly of Three-Dimensional MEMS", *J. Microelectromech. Sys.*, vol. 6, no. 1, March 1997
4. J. H. Comtois, V. M. Bright, M. W. Phipps, "Thermal microactuators for surface-micromachining processes", *Proc. SPIE*, vol. 2642, 10-21
5. W. C. Tang, T. H. Nguyen, R. T. Howe, "Laterally Driven Polysilicon Resonant Microstructures", *Sensors and Actuators*, vol. 20, 1989, 25-32
6. J. H. Comtois, V. M. Bright, "Surface Micromachined Polysilicon Thermal Actuator Arrays and Applications", *Proc. Solid-State Sensor and Actuator Workshop*, 1996, 174-177
7. D. Yan, A. Khajepour, R. Mansour, "Modeling of two-hot-arm horizontal thermal actuator", *J. Micromech. Microeng.*, vol. 13, 2003, 312-322
8. K. S. J. Pister *et al.*, "Microfabricated hinges", *Sensors and Actuators A*, vol. 33, 1992, 249-256
9. "SUMMiT V Five Level Surface Micromachining Technology Design Manual", ver. 3.2, Sandia National Laboratories
10. K. E. Petersen, "Silicon as a Mechanical Material", *Proc. IEEE*, vol. 70, no. 5, May 1982, 420-456